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Technical Memorandum

THE GEOS–II HEAT PIPE SYSTEM AND ITS PERFORMANCE IN TEST AND ORBIT

by R. E. HARKNESS

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY

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THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY
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ABSTRACT

The GEOS-II spacecraft is the first satellite to be equipped with a heat pipe as an integral part of the thermal design. The heat pipe, a device of extremely high effective thermal conductivity, is employed to minimize the temperature differences between transponders located in opposite quadrants of the spacecraft. Measured heat transfer rates through the pipe of as much as 64 watts, together with small temperature gradients on the outside of the heat pipe, are evidence of proper operation. Based on a 145-day observation period, transponder maximum and minimum temperatures show significant improvement over those of GEOS-I.

This work was supported by the National Aeronautics and Space Administration Office of Space Science and Applications under Task I of Contract NOw 62-0604-c.

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I. INTRODUCTION

The heat pipe, a device of extremely high effective thermal conductivity, was invented by Gaugler (Ref. 1). Later, Wyatt (Ref. 2) and Grover (Ref. 3) patented applications of the generic device, and Cotter (Ref. 4) gave a theoretical explanation of its operation. Recently, Deverall and his associates designed an experimental heat pipe module that was orbited on the Atlas-Agena vehicle used for the ATS-A satellite. The results of this experiment indicated that the absence of gravitational forces does not affect the performance of a heat pipe (Ref. 5).

A program to develop a heat pipe for spacecraft temperature control has been in progress for several years at the Johns Hopkins University Applied Physics Laboratory. When it became apparent during the early design stages of GEOS-II that large temperature differences could exist among the various transponders, it was decided to connect the transponders by two heat pipes to minimize these temperature differences. The GEOS-II spacecraft is the first satellite to have a heat pipe incorporated as an integral part of the thermal design. This report describes the design of the heat pipe system and its performance during test and in orbit.

This work was supported by the National Aeronautics and Space Administration Office of Space Science and Applications under Task I of Contract NOw 62-0604-c.

II. SYSTEM DESCRIPTION

A. HEAT PIPES

Two heat pipes, identical in function and differing only in length, were fabricated and installed. As shown in Fig. 1, the heat pipe consists of a section of 6061 T-6 aluminum tubing (1 inch OD and 0.065 inch wall) that is sealed at the ends by welded caps. A wick structure consisting of an annulus of six layers of 120-mesh aluminum

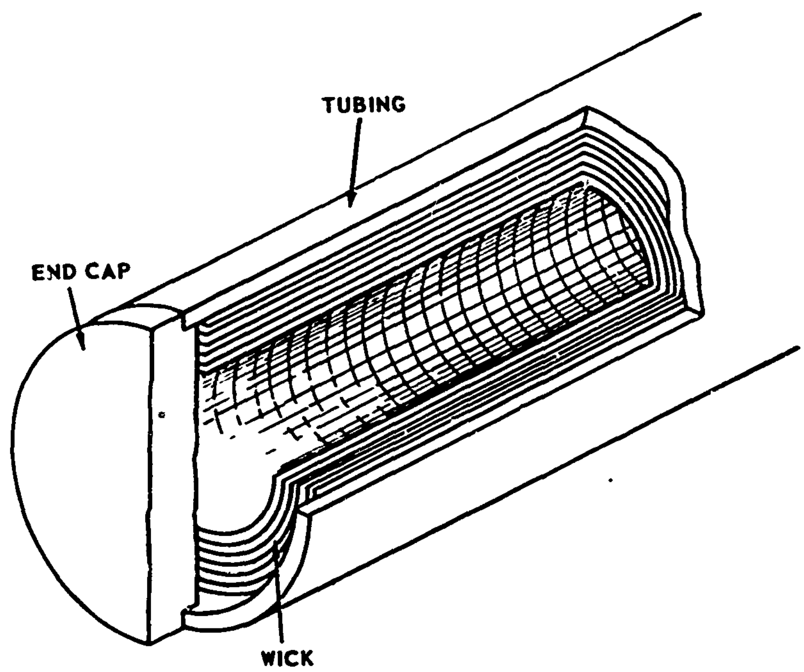

Fig. 1 SCHEMATIC OF HEAT PIPE

wire cloth is in contact with the inside diameter of the tubing. The heat pipe is evacuated by a vacuum pump and charged with slightly more than enough Freon-11 to wet the wick. Freon-11 was chosen for the working fluid because of its low freezing point and because its nonflammable characteristic made it safe to use in a welded structure. A further advantage was its low pressure at the expected operating temperature range. After charging, the pipe is

hermetically sealed by a double seal welded closure to insure the integrity of the pipe. This operation is the most critical of all during the fabrication process. Any leakage path, however small, will ultimately result in leakage of all the working fluid from the heat pipe in the hard vacuum conditions to which it is subjected.

During operation, heat enters one end of the heat pipe and vaporizes some of the fluid. The Freon vapor travels to the cooler end of the pipe, where it condenses. The condensed fluid is returned to the hot, or evaporator, end of the heat pipe by the capillary action of the wick. The result of this closed cycle operation is that large amounts of heat can be transmitted with a very small axial temperature gradient along the outer surface of the isothermal section of the heat pipe.

B. GENERAL ARRANGEMENT

Figure 2 shows the arrangement of the components of the system. The heat pipes, shown by dashed lines, are arranged in a horizontal plane parallel to the XY plane and below the library floor. (The arrangement of the heat pipes in a horizontal plane allows the system to be tested in a 1g environment.) The short heat pipe connects the SECOR (sequential collation of range) unit with the C-band transponders, and the long heat pipe connects the C-band transponders with the range and range rate transponder.

C. CONDUCTION HEAT TRANSFER PATHS

Because of a design requirement to keep GEOS-II as similar to GEOS-I as possible, it was necessary to use long conduction heat transfer paths to and from the heat pipes. These conduction paths represent the greatest portion of the overall thermal resistance of the system. The design approach is illustrated schematically in Fig. 3. A 0.5-inch-thick heat sink plate of aluminum alloy 2024 is mounted to the library wall. The transponder is in turn mounted to the heat sink plate. A thin insulating film between the transponder

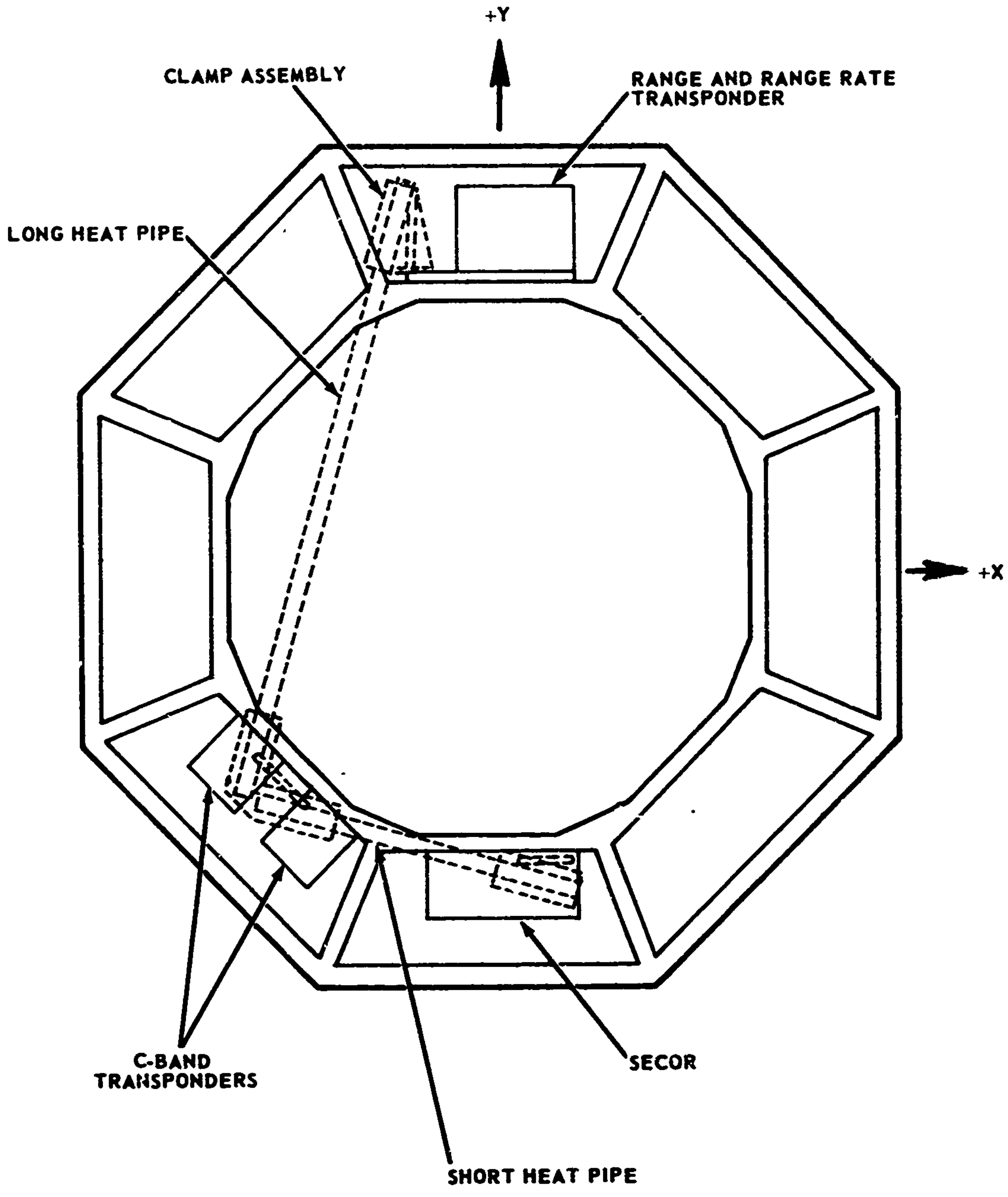

Fig. 2 GENERAL ARRANGEMENT OF HEAT PIPE SYSTEM

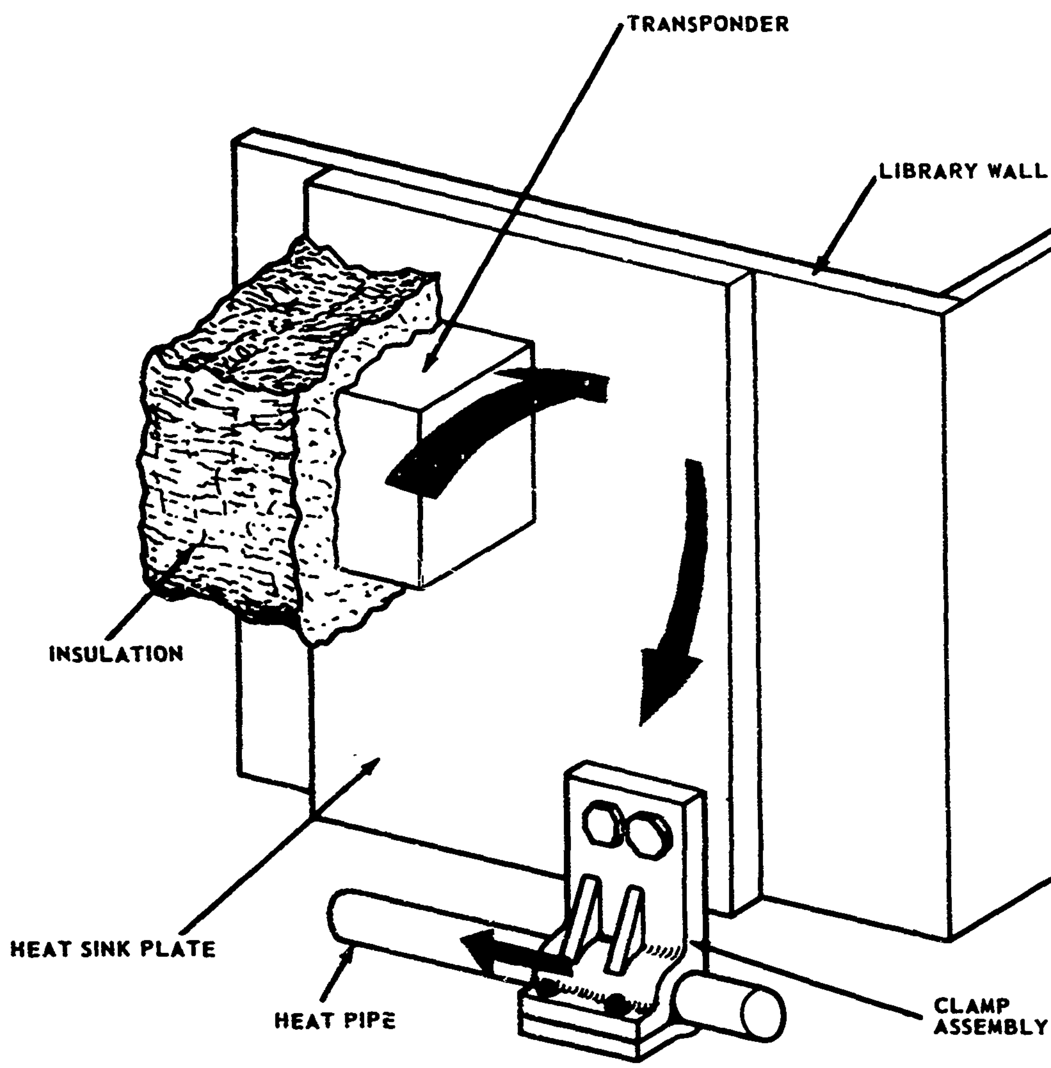

Fig. 3 CONDUCTION HEAT TRANSFER PATHS

and the heat sink plate provides electrical insulation, which slightly increases the thermal resistance. A clamp assembly, bolted near the bottom of the heat sink plate, holds the heat pipe for a distance of 5 inches. Indium foil is used to insure good thermal contact between the heat pipe and the clamp and between the clamp and the heat sink plate. The transponder, clamp assembly, and heat pipe are covered with a multilayer, reflective-type insulation. As shown by the figure, heat generated in the transponder may either be radiated to other parts of the spacecraft or be transferred by conduction to the heat sink plate. Part of the energy reaching the heat sink plate is transmitted to the library wall by conduction, part is radiated to other parts of the spacecraft, and the rest is transferred by conduction to the heat pipe via the clamp assembly.

D. INSTRUMENTATION

Six telemetry channels were allocated specifically for the heat pipes. Four of these channels were used for temperature measurements along the length of the long heat pipe, and one was used for a temperature measurement midway between the extremities of the short heat pipe. Calibrated thermistors were used as the temperature sensors.

The remaining telemetry channel was used for a heat flux measurement. The sensor in this case was a thermopile manufactured by Hy-Cal Engineering Co. that had a rated output of 100 mv at 500 Btu/hr ft^2 thermal input. The sensor is rectangular, approximately 2.25 x 0.5 x 0.080 inches thick. A slot was milled into the flange of the range and range rate clamp assembly to receive the component. Again, indium foil was used for good thermal contact. The output of the thermopile was connected to a specially designed amplifier (Ref. 6) to ensure that the telemetry signal would be adequate in amplitude. The flux sensor/amplifier system was bench-calibrated as a unit. A known amount of electrical power was supplied to a cylindrical heating element held by the clamp assembly, and the heat was removed through that area of the heat sink plate that was in

contact with the range and range rate transponder. The output of the amplifier was read on a digital voltmeter, and heat flux was plotted versus amplifier output to obtain the calibration.

III. PERFORMANCE

A. BENCH TESTS

Bench tests were conducted using the equipment illustrated in Fig. 4. The main pieces of equipment are a refrigerator unit, a cooling tank, and a 24-point temperature recorder. An absolute pressure transducer, together with a wheatstone bridge and voltmeter, measures vapor pressure. Copper-constantan thermocouples, affixed to the exterior of the heat pipe, are used to sense temperature. The condenser end of the heat pipe protrudes through a seal in the cooling tank wall; the evaporator end of the heat pipe is heated by means of a concentric heating element. The heat pipe is completely insulated, with the exception of the condenser.

The refrigerator unit is equipped with a compressor that constantly circulates refrigerant through two evaporators. The main evaporator is located in the cooling tank, and the auxiliary evaporator is in the cabinet. A sensing bulb and a bellows assembly control the temperature of the coolant, which is a mixture of water and antifreeze. When the temperature reaches the control setting, a solenoid valve is energized, diverting the refrigerant from the main to the auxiliary evaporator.

At the conclusion of the start-up transients, the heat pipe exhibits a steady-state behavior in which the section of the pipe between the condenser and evaporator is nearly isothermal. This temperature can be varied by changing the power level, changing the cooling bath temperature, or changing the evaporator or condenser areas. Conditions may also vary if the pipe is not fully evacuated prior to being charged with the fluid or as a result of a leak that allows the fluid to escape or air to flow into the pipe. Figure 5 shows the mean heat pipe temperature as a function of input power level. The mean temperature increases linearly with power level. The effect of bath temperature is also shown. For the conditions of the experiment, a change of bath temperature of 6.5°F resulted in a mean heat pipe temperature difference of about 6°F.

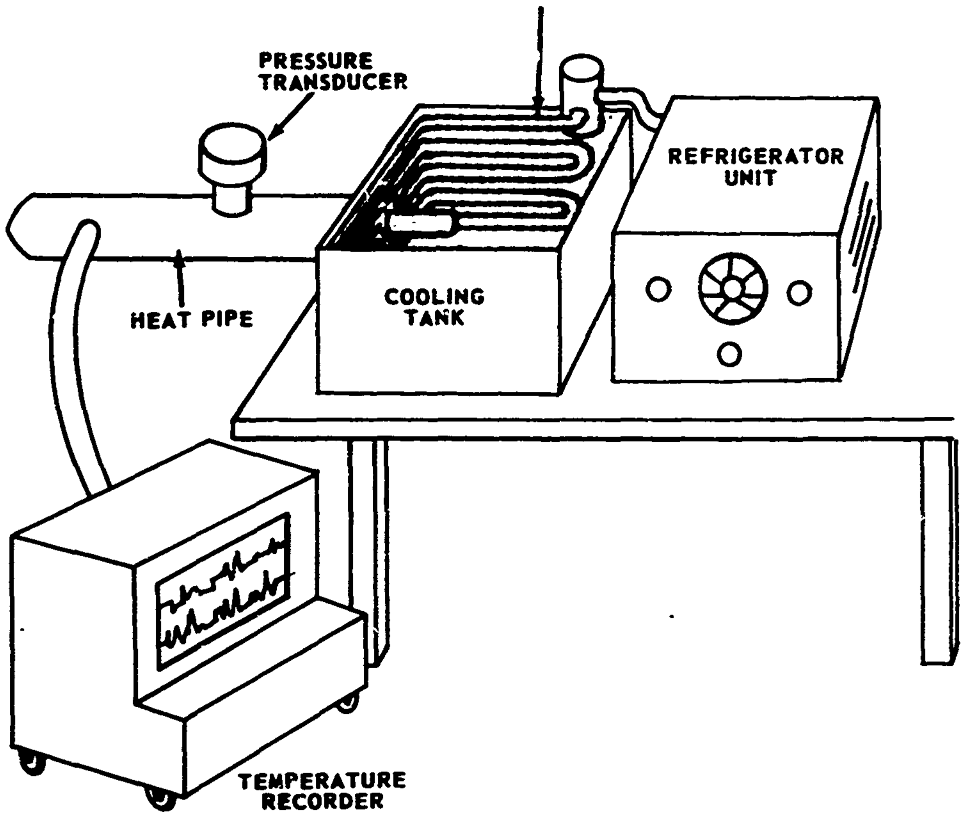

Fig. 4 EQUIPMENT FOR BENCH TESTS

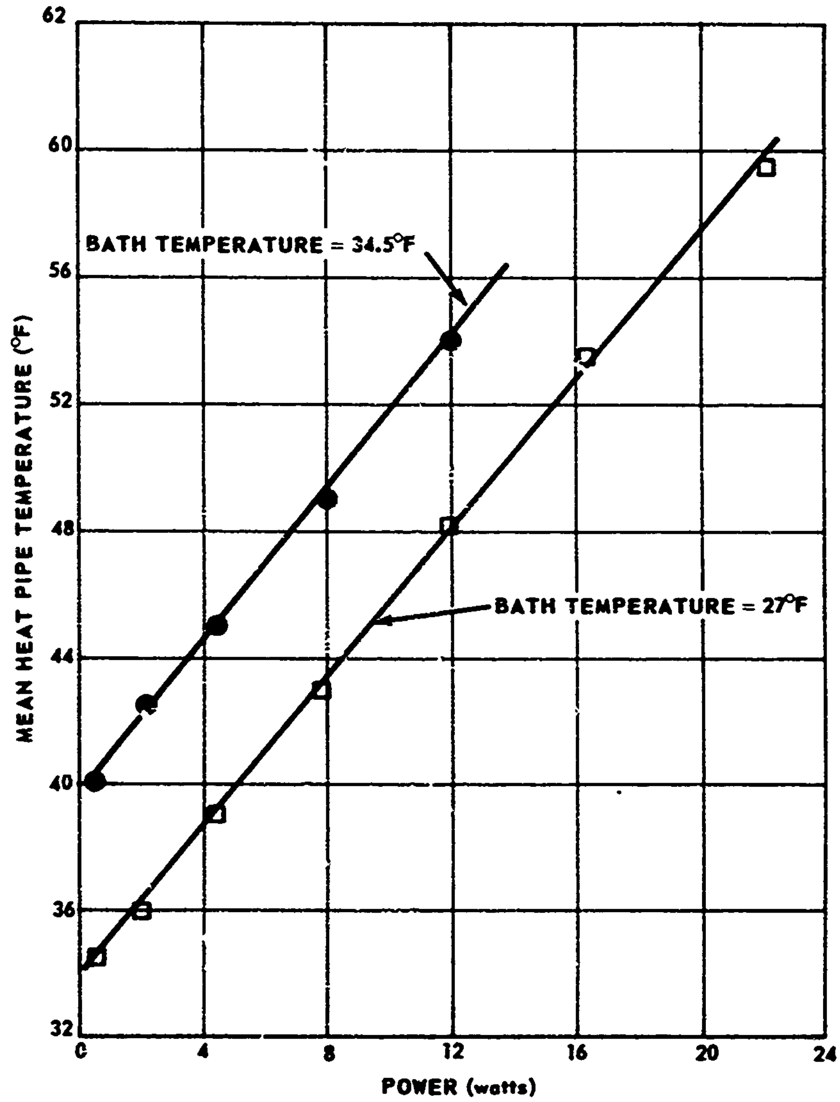

Fig. 5 MEAN HEAT PIPE TEMPERATURE AS A FUNCTION OF INPUT POWER LEVEL

B. THERMAL VACUUM TESTS

The GEOS-II spacecraft was subjected to three basic types of thermal vacuum tests: maximum Q, corresponding to the hottest expected conditions to which the satellite would be exposed; minimum sun, corresponding to the coldest expected conditions; and hang-up, which simulates the maximum expected thermal gradients across the satellite. The maximum Q case occurs 10 days after transition from less than 100% sunlight exposure to 100% sunlight. The solar constant, albedo, and power generated by the solar array were assumed to be maximum for this case. The minimum sun case simulates the resultant solar exposure when the orbit normal is perpendicular to the earth-sun line. The solar constant, albedo, and power generated by the solar array were assumed to be minimum for this case. In the hang-up case, the orbit normal is parallel to the earth-sun line, and the same side of the satellite is always facing the sun.

Figures 6, 7, and 8 show heat pipe system performance during thermal vacuum testing of the three cases. Note that the modes of satellite operation are slightly different: all three transponders were on for the hang-up case (Fig. 8), whereas only the SECOR was on for the minimum sun and maximum Q cases (Figs. 6 and 7). The small temperature gradients along the outside surface of the long heat pipe are evidence of proper operation.

In Fig. 6, heat flows toward the C-band transponders from both the range and range rate and SECOR transponders. The temperatures of the transponders and heat pipes are relatively low as a result of the simulated low exposure to sunlight. The SECOR temperature is largest owing to the fact that this component was energized and was, therefore, generating heat.

Figure 7 shows the results for the maximum Q case, again with only the SECOR energized. The transponder temperatures are the maximum of the three cases. In this test, heat was transferred from the SECOR through

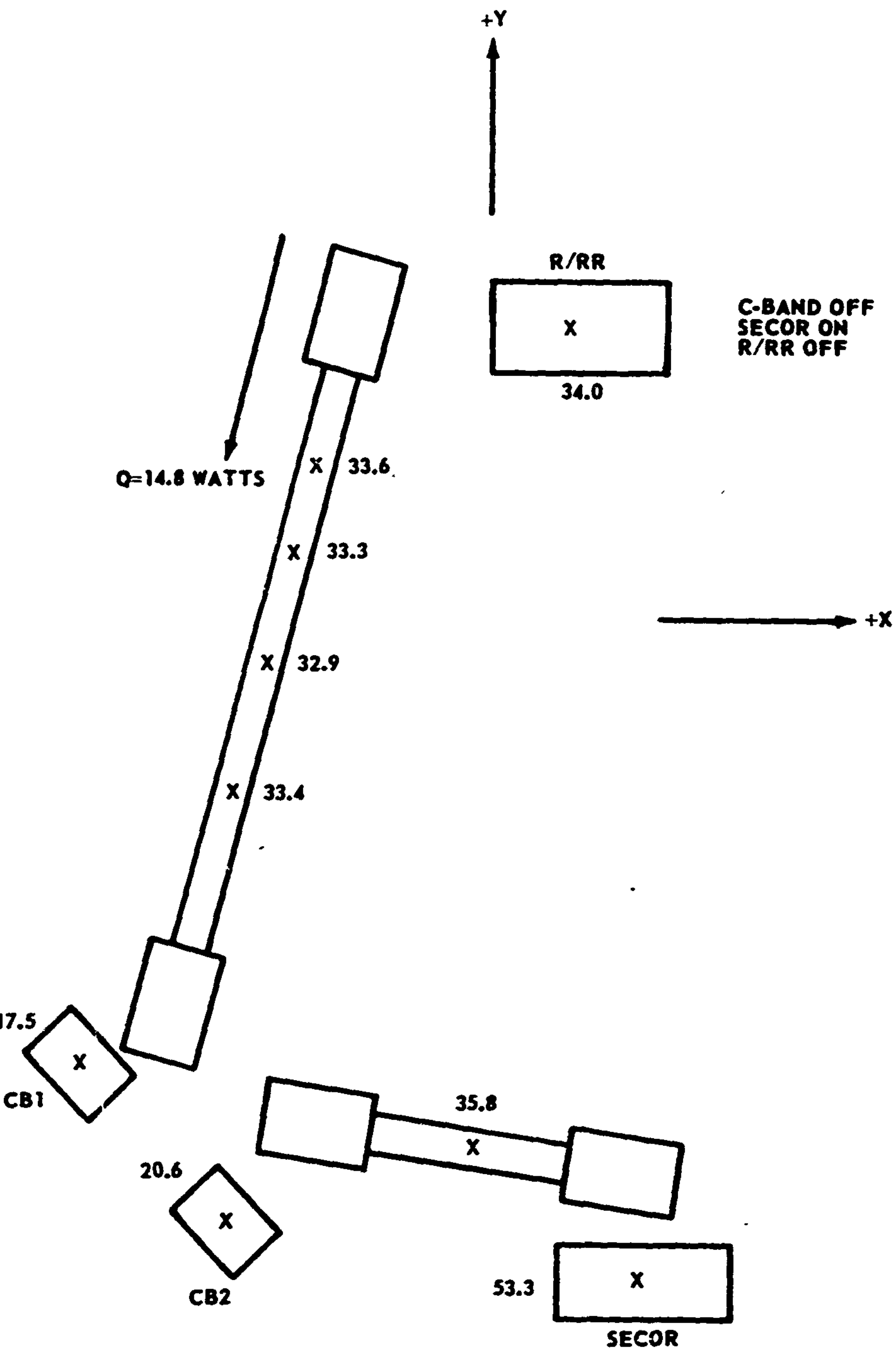

Fig. 6 HEAT PIPE SYSTEM PERFORMANCE DURING THERMAL VACUUM TESTS—MINIMUM SUN CASE

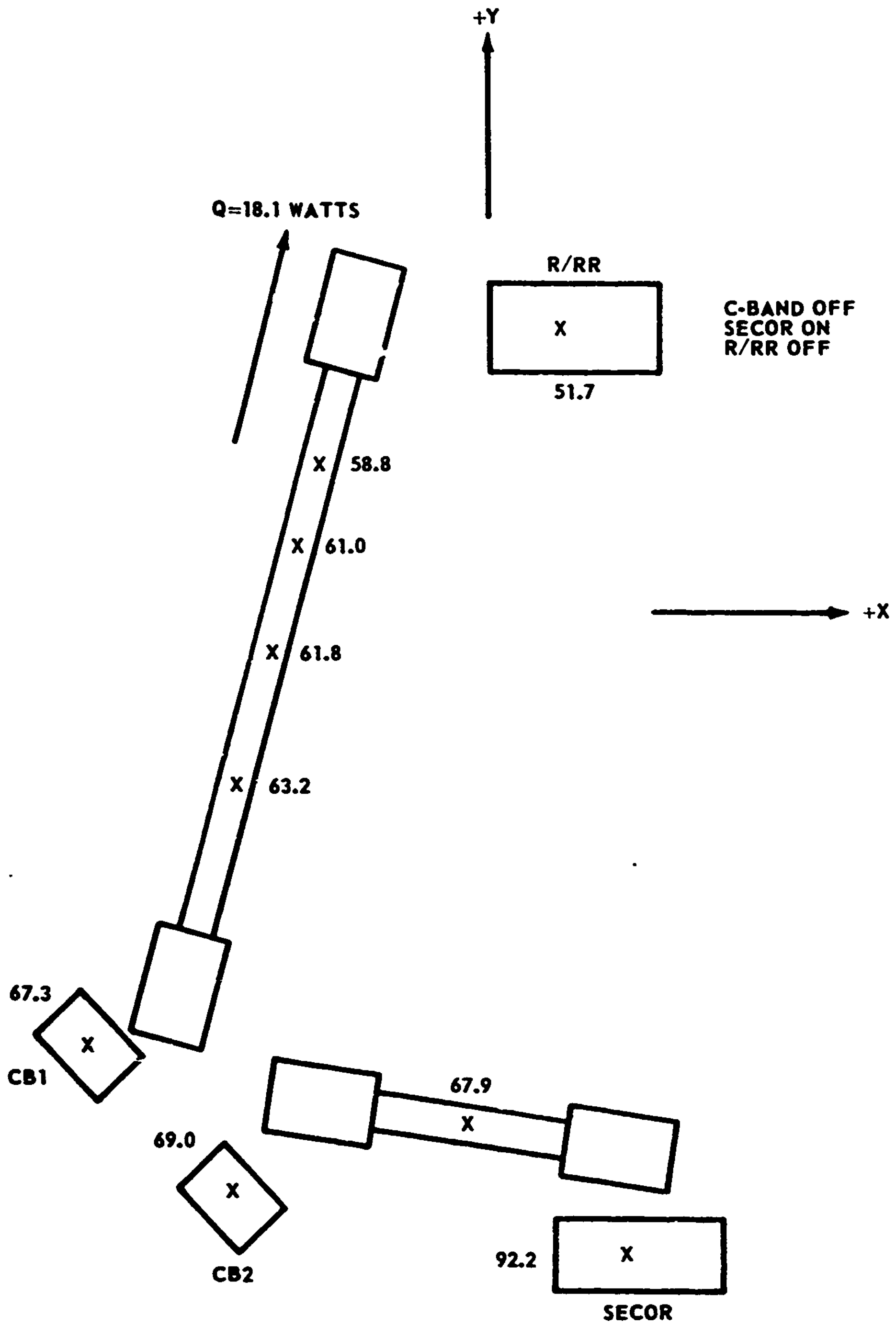

Fig. 7 HEAT PIPE SYSTEM PERFORMANCE DURING THERMAL VACUUM TESTS–MAXIMUM Q CASE

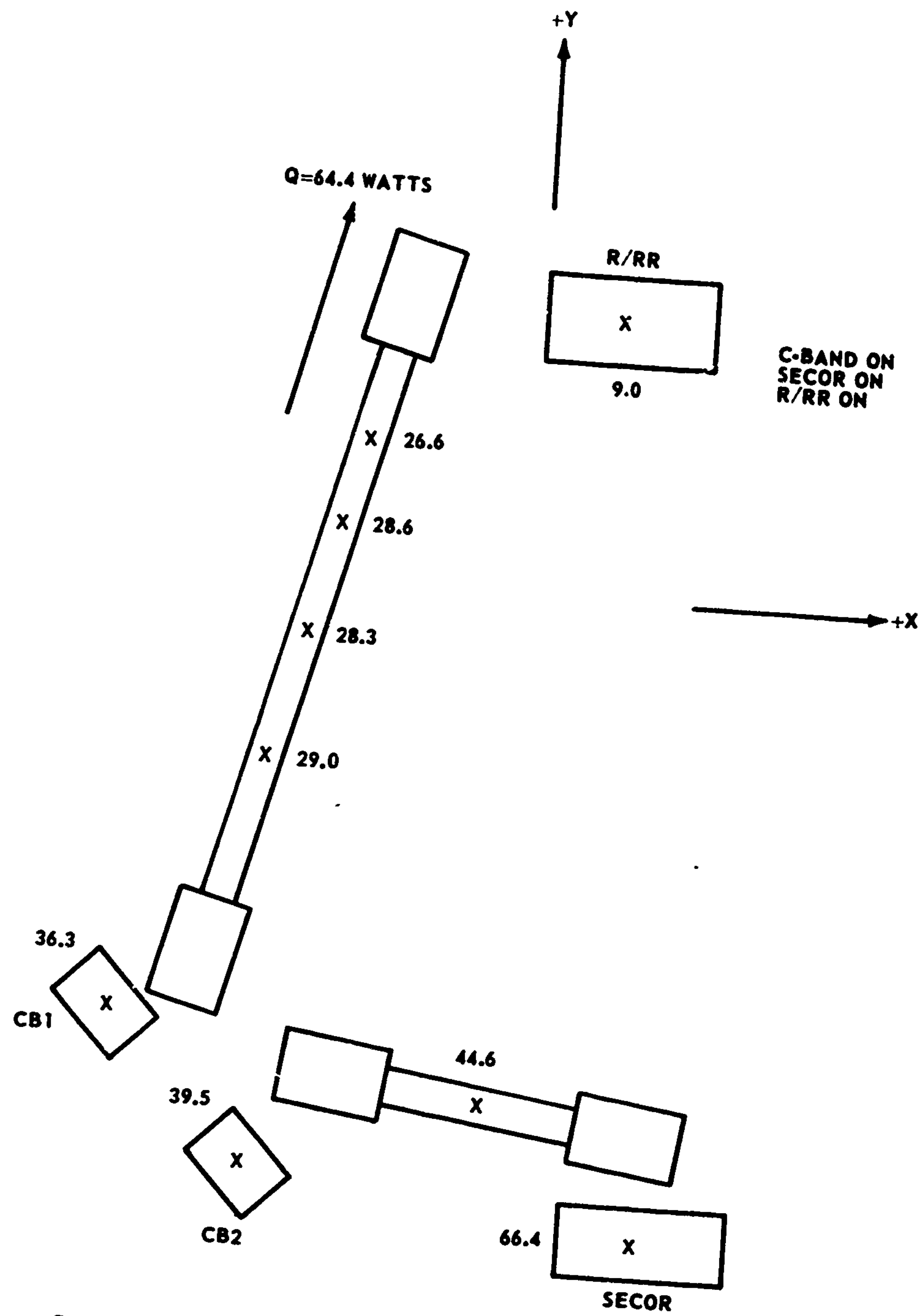

Fig. 8 HEAT PIPE SYSTEM PERFORMANCE DURING THERMAL VACUUM TESTS–HANG-UP CASE

the short heat pipe to the C-band transponders and thence through the long heat pipe to the range and range rate transponder. A total of 18.1 watts of heat flux was measured by the flux sensor.

Figure 8 shows the hang-up case with all transponders on. The maximum amount of heat was transmitted in this case, and a maximum temperature difference of 57.4°F between the SECOR and the range and range rate transponder occurred.

A series of tests was also conducted to show the effect of heat pipe failure on thermal performance. To accomplish this, the spacecraft was tilted 10° about the x-axis to defeat the action of the heat pipe. The tests were conducted in such a manner that the C-band transponders were always hotter than the range and range rate transponder. The C-band transponders were at a higher elevation than the range and range rate transponder, and the capillary pumping action was insufficient to overcome the gravity head. Therefore, the heat pipe fluid collected in the lower end, and all heat transferred by the pipe was by conduction through the wick and tubing.

Figure 9 shows the temperature gradient along the long heat pipe while the spacecraft was in the tilted configuration. At 0521 the temperature difference between the sensors that were farthest apart was about 30°F. At this time, the range and range rate transponder was interrogated, causing heat to flow in the opposite direction. In this case, gravity aided the return of the condensed fluid. The temperature profiles taken at 0615, 0732, 0900, and 1103 show the rate at which the initial large temperature gradient was reversed as the heat pipe attained steady state. It is interesting to note that the measured heat flux increased from an initial value of 14.8 watts to 75.5 watts at 1103. This resulted from the fact that, initially, the Freon vapor condensed very close to the range and range rate clamp. As the outside of the heat pipe was warmed by this condensation, the vapor traveled farther and farther before the slight vapor superheat was removed and condensation occurred. As a result, more of the fluid near the

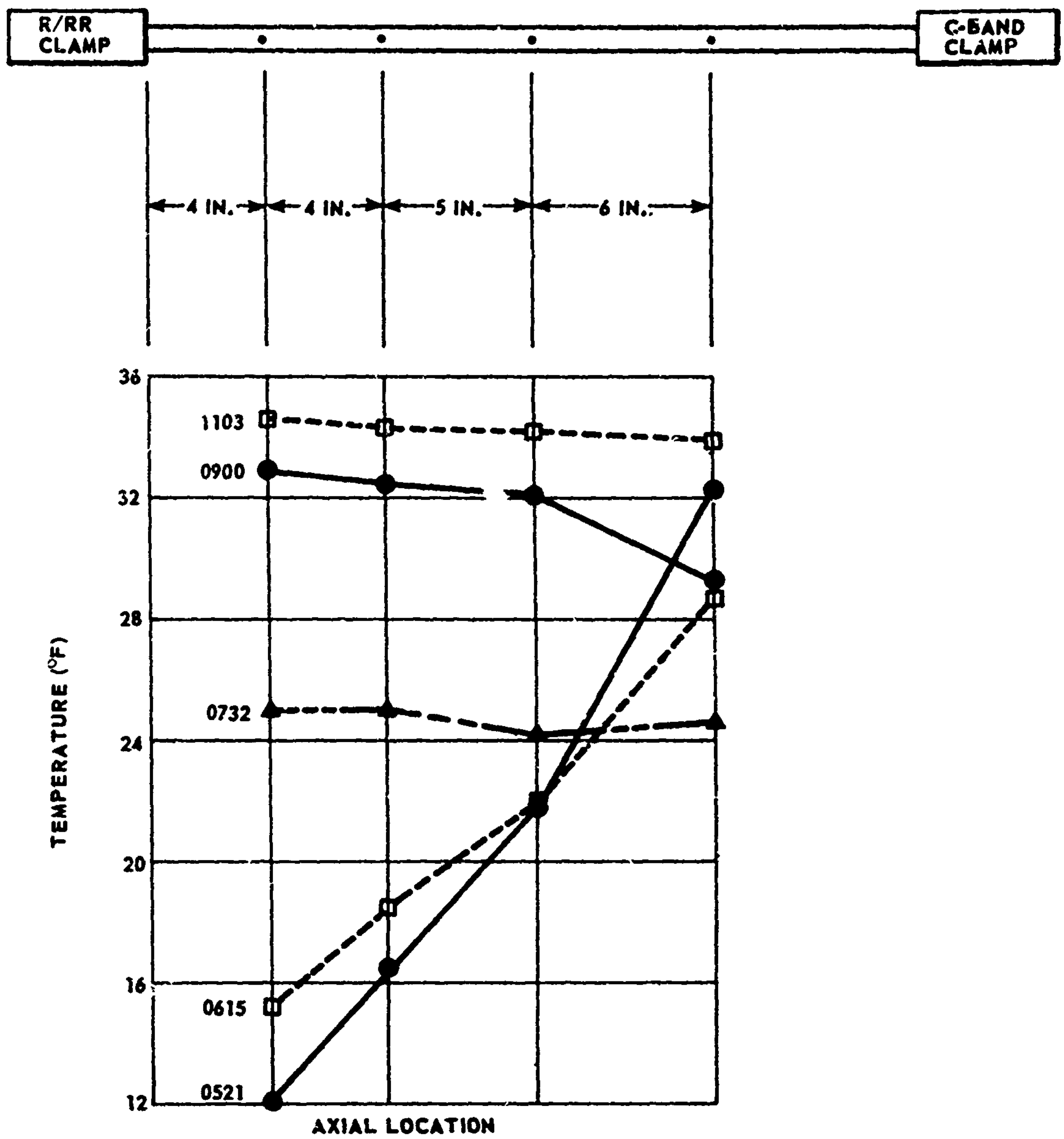

Fig. 9 TEMPERATURE GRADIENT REVERSAL DURING THERMAL VACUUM TESTING

range and range rate end of the pipe, which had flooded this (evaporator) portion of the pipe, vaporized. The evaporator area therefore increased and the heat transfer rate improved until, finally, normal operation was restored.

C. PERFORMANCE IN ORBIT

As mentioned previously, the purpose of the heat pipe system is to minimize the temperature differences among the transponders. Although the temperature difference may be made smaller by energizing the coldest transponder or by not energizing the hottest transponder, such a scheme imposes a constraint on satellite operations. Further, it is even possible that the transponder might get so cold that it could not be operated. For these reasons, the heat pipe system was installed on the spacecraft.

Table I compares the extreme temperatures and temperature differences between the SECOR and range and range rate (R/RR) transponder covering the latter part of 1965 and all of 1966 for GEOS-I and for the 145 day period between days 16 through 160 of 1968 for GEOS-II. (The C-band transponders were not included in this comparison since GEOS-I was not equipped with them..) Based upon this limited sample size for GEOS-II, considerable improvement is noted in all respects.

Table I

Comparison of Transponder Temperature Extremes

	SECOR Temp. (°F)		R/RR Temp. (°F)		Maximum ΔT (°F)	
	Max.	Min.	Max.	Min.	SECOR– R/RR	R/RR– SECOR
GEOS-I	110	6	138	12	65	95
GEOS-II	83	34	79	37	36	38

Of particular note is the large maximum temperature, 138°F, of the GEOS-I range and range rate transponder and the maximum temperature difference of 95°F. These data points were taken during January 1966. Calculations made for GEOS II predicted a maximum temperature difference of 92°F without the heat pipe system and 32°F with the system (Ref. 7). Tests subsequently showed that the thermal resistance of the clamp assemblies was somewhat higher than the value used in the calculations and that, hence, the maximum temperature difference would exceed the predicted 32°F.

The effect of the heat pipe system on reducing the maximum temperature among the transponders may also be seen in Figs. 10 through 13. Figure 10 shows the mean maximum temperature difference, averaged daily, as a function of time. The trend, shown by the dashed line, is seen to be slowly rising. This trend is believed to be caused by more frequent transponder operation and the environmental conditions. The environmental conditions for most of this time period closely approximate the maximum Q case of the thermal vacuum test (Fig. 8). Figure 11 shows the comparable data for day 100 through day 160. During this period, satellite operations became more routine, and the resulting mean maximum temperature difference was computed to be 7.4°F with a standard deviation of 2.5°F.

Figure 12 shows the daily differences between the mean temperatures of the long and short heat pipes. The mean was calculated to be +0.4°F with a standard deviation of 3.5°F. Good agreement is shown with Fig. 10, since the mean temperature of a heat pipe lies somewhere between the temperatures of the transponders that it connects. Inasmuch as the axial temperature gradient along a heat pipe is small, this figure also shows that the clamps represent the largest thermal resistance in the system. Figure 13 shows comparable data for day 100 through day 160. These data prove the satellite to be quite stable thermally. The mean and standard deviation of the heat pipe temperature differences during this period were calculated to be -0.1°F and 1.6°F, respectively.

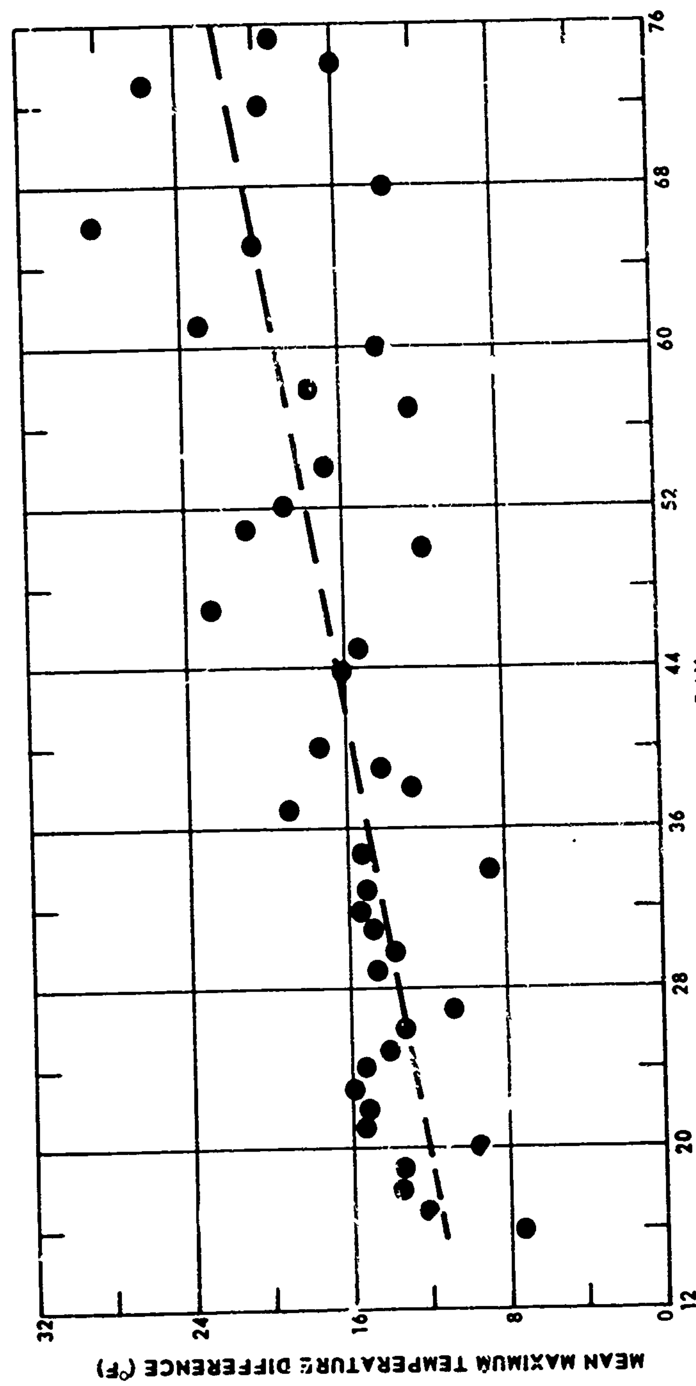

Fig. 10 MEAN MAXIMUM TRANSPONDER TEMPERATURE DIFFERENCE AS A FUNCTION OF TIME, DAYS 16 THROUGH 76

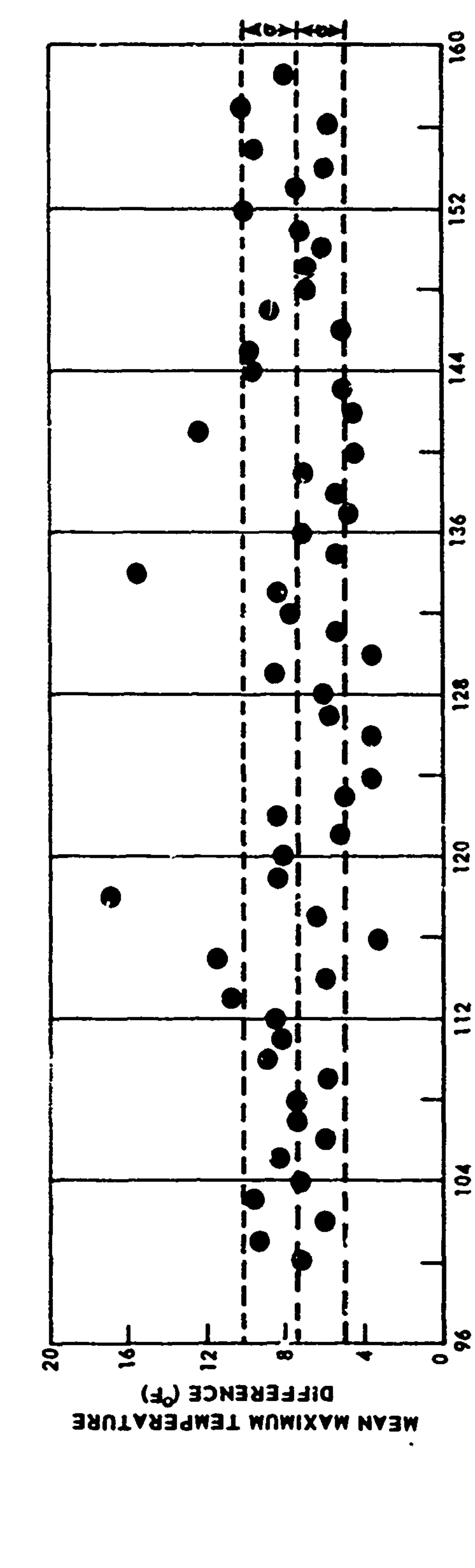

Fig. 11 MEAN MAXIMUM TRANSPONDER TEMPERATURE DIFFERENCE AS A FUNCTION OF TIME, DAYS 100 THROUGH 160

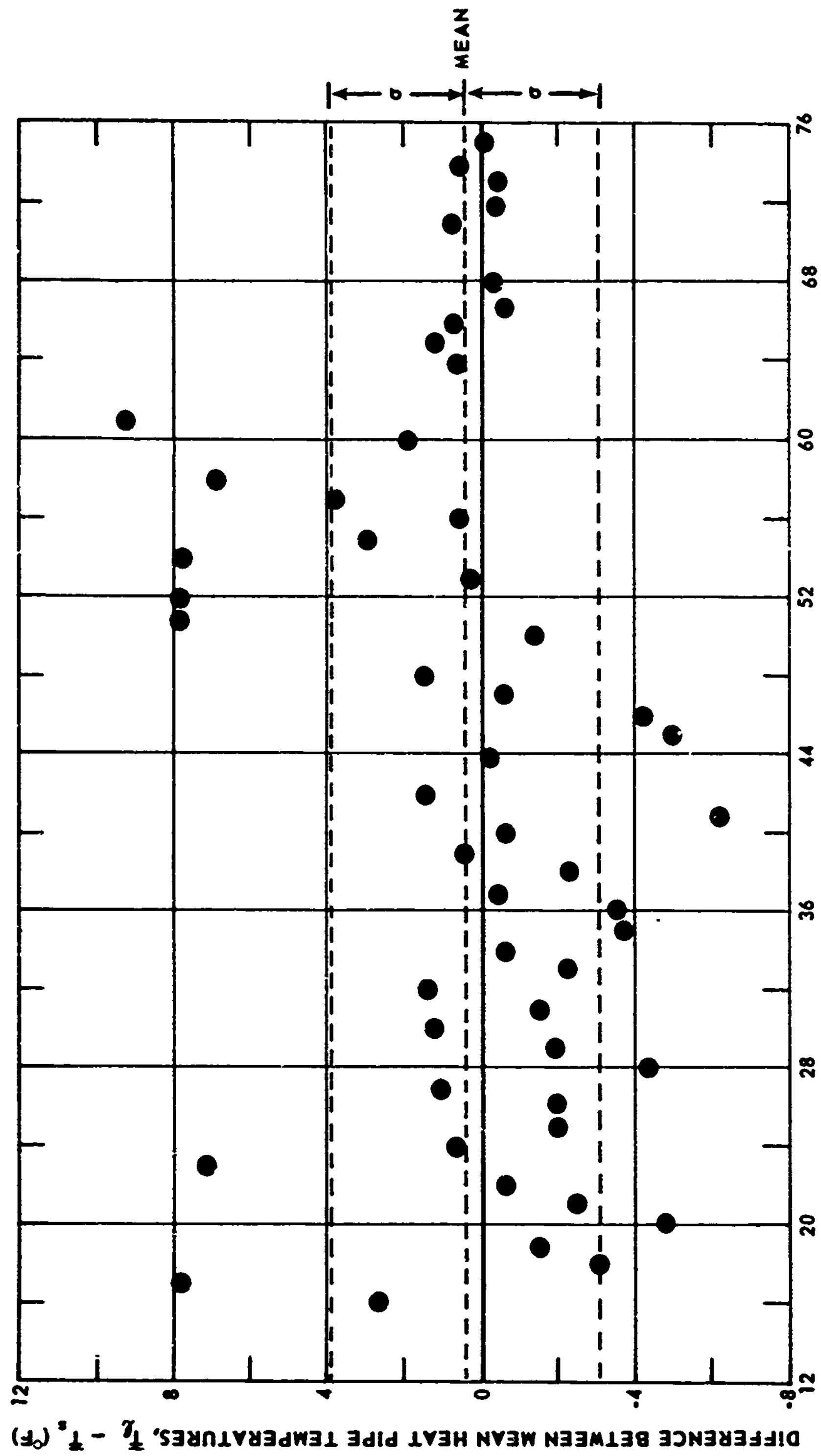

Fig. 12 DAILY VARIATION OF DIFFERENCE BETWEEN MEAN HEAT PIPE TEMPERATURES, DAYS 16 THROUGH 76

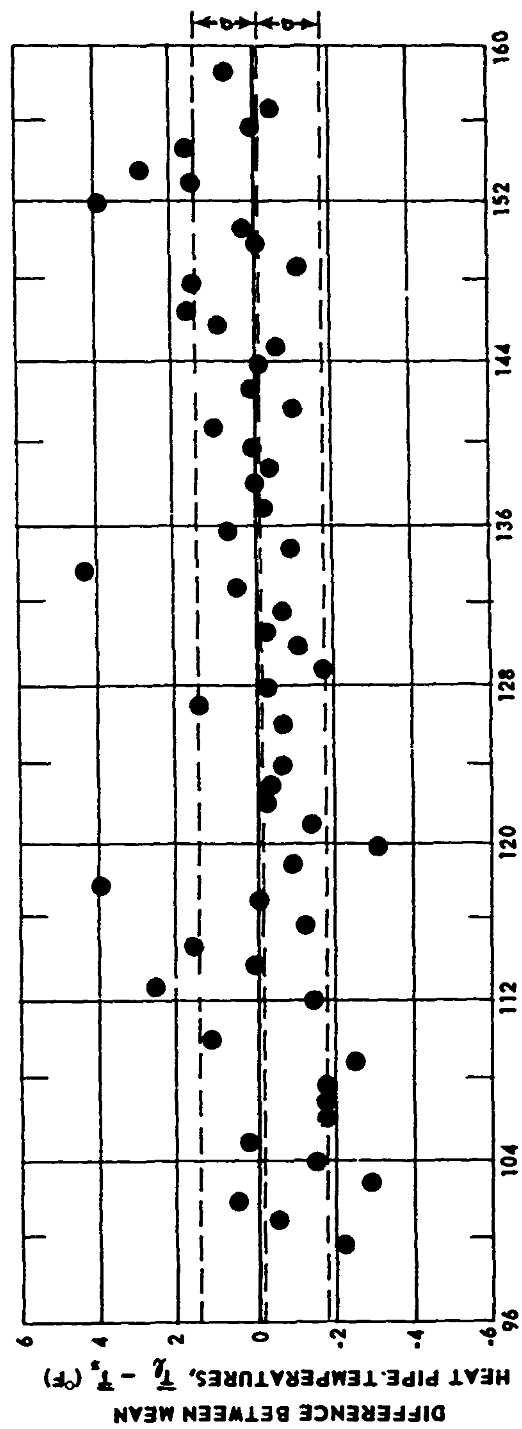

Fig. 13 DAILY VARIATION OF DIFFERENCE BETWEEN MEAN HEAT PIPE TEMPERATURES, DAYS 100 THROUGH 160

Figures 14 and 15 show the performance of the heat pipe system in orbit. These sets of data were selected because they represent the greatest measured heat transfer rates during the period of observation. In Fig. 14, all three transponders were energized, and a total of 43.5 watts was measured at the flux sensor. A temperature gradient of 1.7°F was measured between the two most remote thermistors on the long heat pipe; the maximum transponder temperature difference was 26.9°F.

Figure 15 illustrates a case where the heat flow is in the opposite direction, that is, from the range and range rate transponder toward the C-band transponders. As is shown, a power level of 64.0 watts was measured by the flux sensor, with a temperature gradient of 3.5°F being measured between the most remote thermistors on the long heat pipe. The maximum transponder temperature difference is 25.3°F.

It was shown previously in Section III, B that the heat pipe can act to reverse an axial temperature gradient on the outside of the heat pipe. In orbit, such a condition occurs when the spacecraft orientation with respect to the sun changes radically or whenever a colder transponder is energized. Figure 16 is an example of such a temperature gradient reversal. As a result of the C-band transponders being hotter than the range and range rate transponder, an initial gradient of 1.9°F existed between the two most remote thermistors. The range and range rate transponder was then energized, causing the external heat pipe temperature gradient to reverse. Approximately 18.8 watts were being transmitted through the pipe when the last data were obtained.

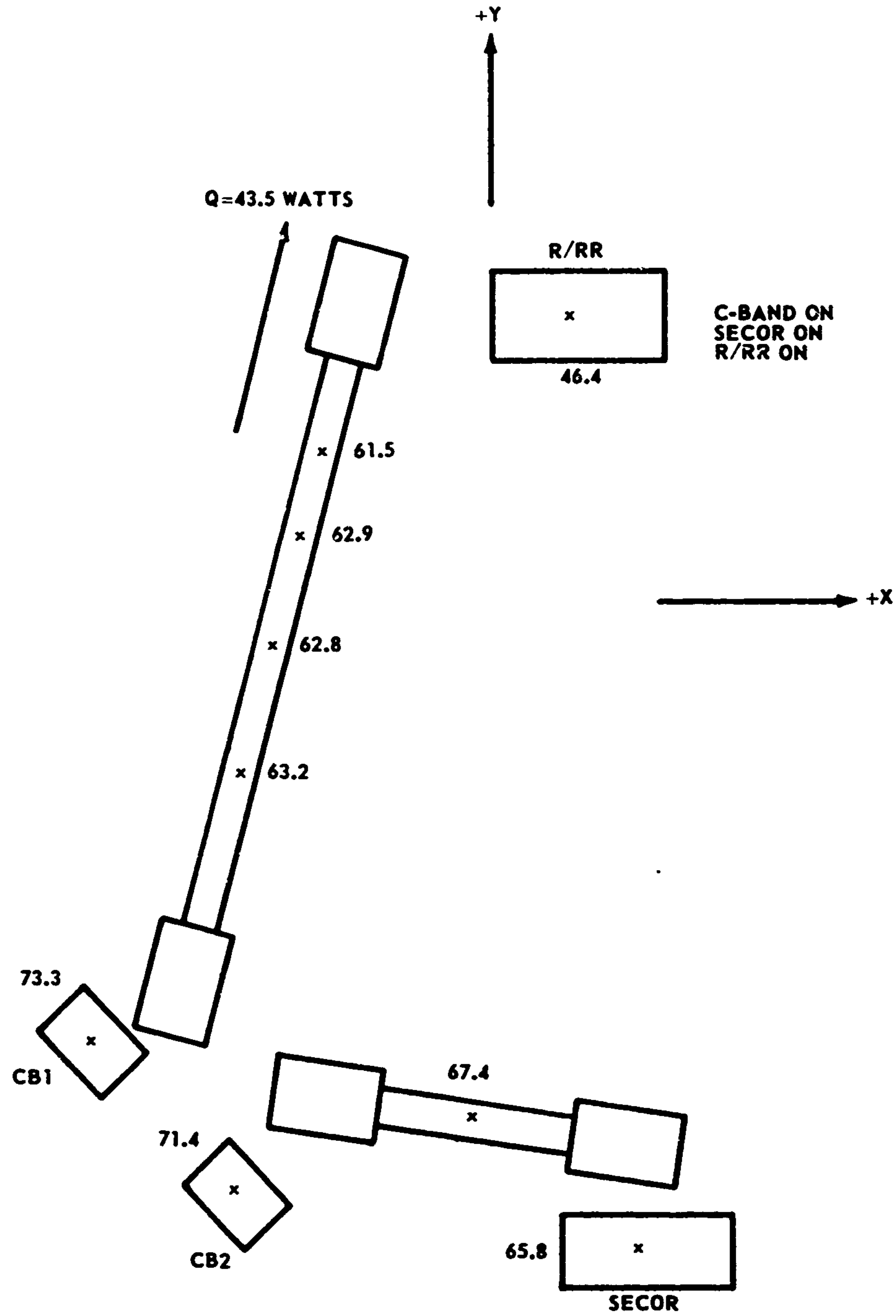

Fig. 14 PERFORMANCE OF HEAT PIPE SYSTEM IN ORBIT, DAY 40 AT 1243

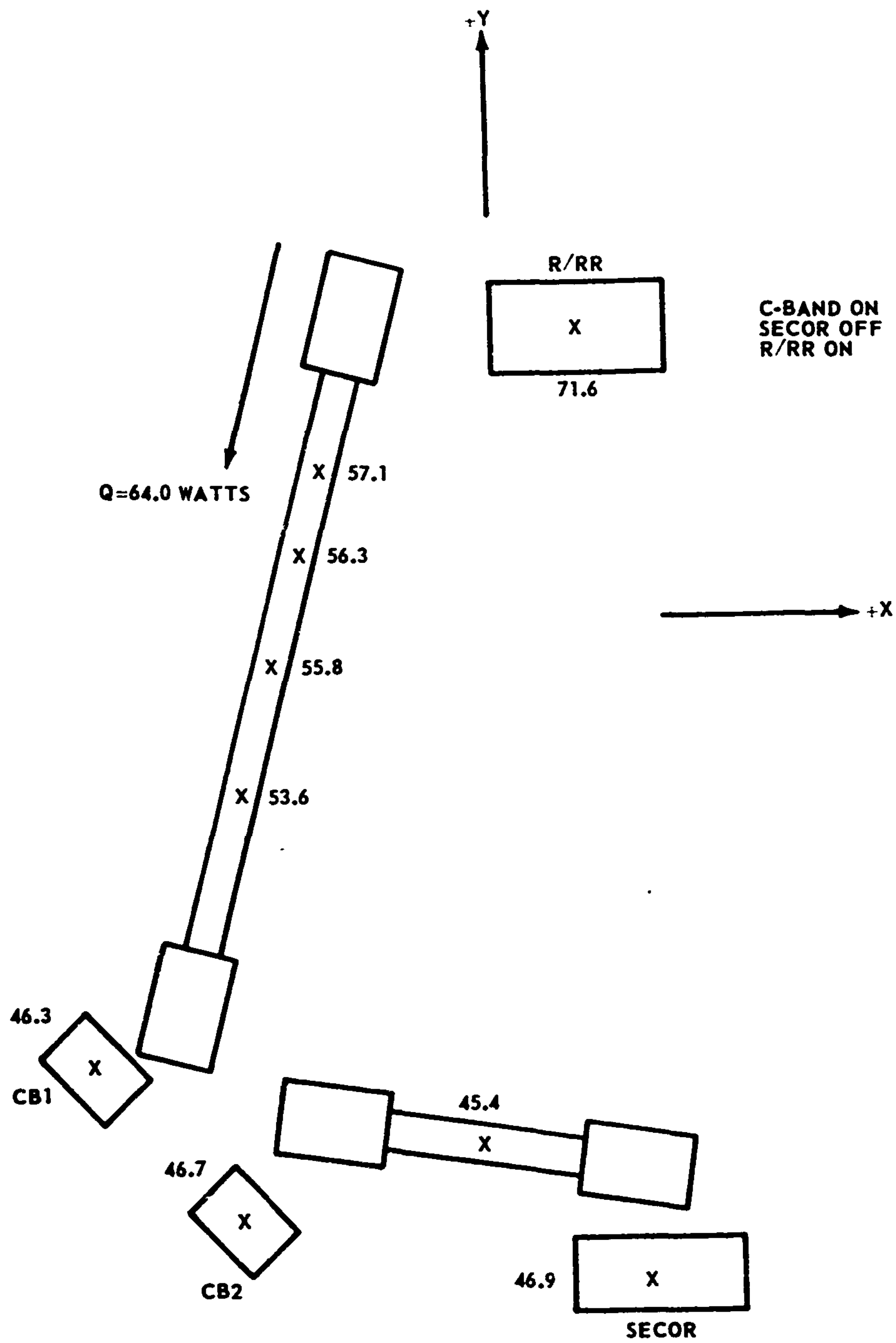

Fig. 15 PERFORMANCE OF HEAT PIPE SYSTEM IN ORBIT, DAY 51 AT 0056

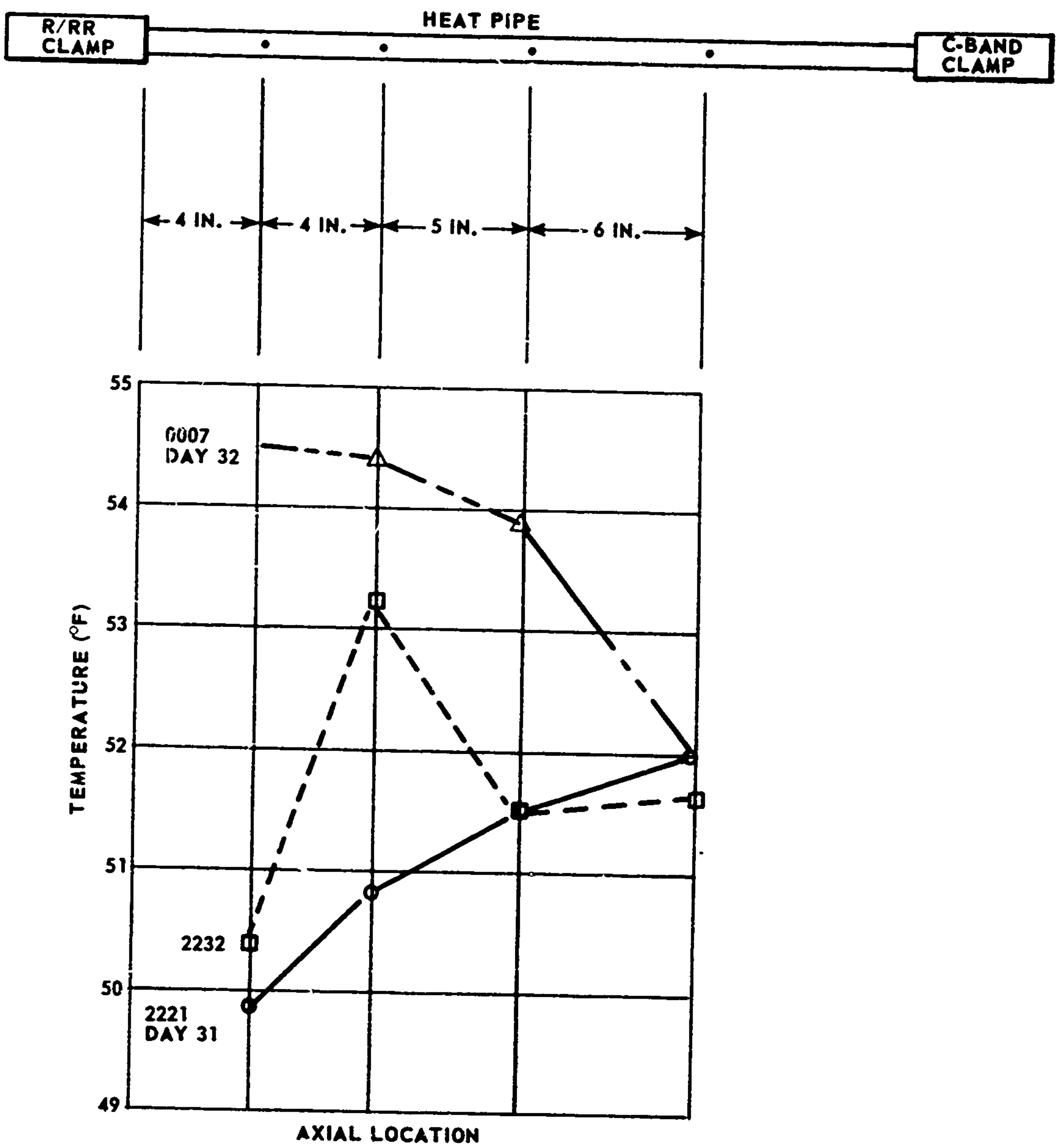

Fig. 16 TEMPERATURE GRADIENT REVERSAL IN ORBIT

IV. CONCLUSIONS

1. During the period of observation, both heat pipes performed normally.

2. Heat fluxes of as much as 64 watts have been transmitted.

3. The range between the maximum and minimum transponder temperatures for the 145 day period of GEOS-II observations was considerably smaller than the range observed for GEOS-I over a much longer period. Further observation of GEOS-II is required before a firmer conclusion may be drawn.

4. Reversal of the heat pipe axial temperature gradient has been observed both in thermal vacuum tests and during orbit.

5. The mean difference between the heat pipe temperatures was small during the period of observation. As a result, it is concluded the heat pipe system performance was not biased either by spacecraft attitude or by operation of the transponders.

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The impetus for using a heat pipe system as an integral part of the thermal design of GEOS-II was provided by Mr. Robert E. Fischell and was based upon a suggestion by Mr. S. E. Willis. Their contributions to the incorporation of the system into the GEOS-II design are gratefully acknowledged.

In addition, special mention should be made of the capable efforts of Mr. Kenneth E. Miller for the design of of the thermopile amplifier and of Mr. William C. Denny for fabricating and testing the heat pipes, and the exceptional services of our able secretaries, Mrs. Solveig L. Smith and Miss Joyce Freeburger.

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13. ABSTRACT

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